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NASA New Technology Report

TITLE: Location of sources of radiation using a weighted hyperbolic technique

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SECTION 1 - DESCRIPTION OF THE PROBLEM THAT MOTIVATED THE TECHNOLOGY DEVELOPMENT

A. General Description of Problem Objective

The specific problem objective was to locate the sources of radiated electric field from lightning using an overdetermined set of measurements of time-of-arrival. A similar problem exists for epicentral sources in earthquake location, acoustic sources of thunder, and terrestrial navigation using LORAN and GPS.

B. Key or Unique Problem Characteristics

A unique problem characteristic for ground-based time-of-arrival systems is that established techniques have difficulty in locating sources close to the plane containing the measurement stations.

C. Past History /Prior Techniques

The usual technique for finding parameters from overdetermined measurements is to minimize the sum of the squares of the weighted measurements. An application of this technique to finding source locations and times-of-occurrence from measurements of times-of-arrival is described in Peters and Crosson (1973). An alternative method is to consider all possible combinations of minimally-determined sets of measurements (that is, four at a time in order to find the parameters x,y,z, and t) and choose the combination that gives the smallest error (for example, Proctor (1971), Poehler and Lennon (1979)).

Descriptions of related systems and techniques are given in various patents relating to lightning location by Lennon and Poehler (as described in Poehler and Lennon,(1979), by Bent (Atlantic Scientific Inc.) (see, for example, Bent and Casper (1985), and by Lightning Location and Protection Inc. (as described in Krider et al., (1976)).

D. Limitations of Prior Technique

In the case of measurement stations in a plane (ground level) and sources close to this plane, the usual minimization technique described in Peters and Crosson (1973) is unreliable unless great care is taken to choose a first guess and to avoid local minima (see the description in Hager and Wang, 1995). Further, it only gives a single estimate of the best estimate of the set (x,y,z,t) whereas in practice the best estimate of each parameter independently may be desired. For example, in order to determine the best estimate of the vertical velocity of consecutive sources, we need to find the best estimates of z and t. By considering the measurements in minimally determined sets, that is four at a time, we can always find a solution (that may involve an imaginary height) but the weighting for each parameter found this way is not obvious. The straightforward technique would be to weight each estimate (that is, from a particular combination of four measurements) by the inverse of the variance in that estimate. Since the weighting factor is a sensitive function of position, this particular technique is subject to considerable error in the weighting factor when a bad estimate falls in a location corresponding to a high weighting factor.

SECTION II TECHNICALLY COMPLETE AND EASILY UNDERSTANDABLE DESCRIPTION OF NEW TECHNOLOGY THAT WAS DEVELOPED TO SOLVE THE PROBLEM OR MEET THE OBJECTIVE

Refer to enclosed paper "System for locating the sources of wideband dE/dt from lightning" by Thomson, Medelius and Davis.

SECTION III - UNIQUE OR NOVEL FEATURES OF THE TECHNOLOGY AND THE RESULTS (OR BENEFITS) OF ITS APPLICATION

A. Novel or unique features

The novel feature of the technique is that we simultaneously find the best estimates of (x,y,z) from all possible combinations of time-tag measurements taken four at a time using different weighting factors for each parameter. Time tags are found as the mean of three times - corresponding to the leading-edge half width, peak, and falling-edge half-width - so that time-tag errors can be determined, as described in Thomson et al. (1994). The procedure for obtaining (x,y,z) is explained on p. 22,796 in Thomson et al. (1994), where Equations (3),(4), and (5) are solved simultaneously. These equations are solved using iterative techniques, convergence being extremely rapid.

A key concern for lightning sources is whether electric field pulses recorded at different stations can be regarded as radiating from the same point source or whether the source is distributed in space. For a distributed source the pulse waveshapes are likely to be different at different stations and location accuracy will be consequently degraded. One theory, the transmission line theory, predicts that sources of wideband electric field pulse radiated from in-cloud lightning processes may effectively radiate from a point source (for example, Le Vine and Willett,1992), and, as a corollary, that waveshapes recorded at different stations have the same waveshape. Other theories predict that sources cannot be regarded as point radiators (e.g. Thottappillil and Uman,1994). Before our experiment no previous multiple-station measurements had sufficient linearity and bandwidth to show that the agreement was as close as we have found, of the order of nanoseconds. Further, similar measurements made by Proctor (1971,1981) indicated that sources of VHF pulses were distributed over several hundred meters in a "radio diameter". By determining that dE/dt pulses have very similar waveshapes at different stations, we have substantiated the transmission line theory for in-cloud sources and verified that the radiation sources may be regarded as point sources and located accurately using time-of-arrival methodology.

B. Development or conceptual problems

The major conceptual problem was how to obtain a single best estimate of each of the parameters x,y,z, and t given that there are a number of estimates, one set from each of the possible combinations involving four stations. For example, if there are five measurements then there are ${}^4C_5$, that is five, sets of (x_j,y_j,z_j,t_j) obtained from the measurements four at a time. Our initial approach was to find the weighted mean for each parameter using the inverse of the appropriate variance as a weighting factor. In the final technique we still use this as an initial guess, as defined in Eq. (8) on p 22,796 in Thomson et al. (1994). From an analysis of data taken by the system described in Thomson et al. (1994), we found that the weighting factor (for example,) $1/\sigma_{xj}^2(x_j,y_j,z_j)$ was unreliable. For example, if a source is in a location where variances for all combinations are relatively high, any combination that gives an estimate in a location corresponding to smaller variances will have an artificially high weighting. This is particularly important for estimates of z (height) for sources near ground. Instead of, for example, $1/\sigma_{xj}^2(x_j,y_j,z_j)$, the weighting factor needed to be $1/\sigma_{xj}^2(x_s,y_s,z_s)$, where (x_s,y_s,z_s) is the actual (unknown) source location. Hence we use $1/\sigma_{xj}^2(x,y,z)$ as the weighting factor where (x,y,z) is the best estimate and is found iteratively. We term this the "weighted hyperbola" technique.

A further concern was whether the variances found using established techniques (for example, as described in Clifford (1973)) were applicable to locations found using weighted hyperbolas, since in the Clifford procedure the assumption is made that the best estimates are found using a single least-squares minimization. While suitable variances could also be found using simulated random errors, the Clifford procedure gives an analytical expression. We tested its suitability by comparing errors using the two techniques, as described in the next section.

C. Operating characteristics, test data

Results are described in Thomson et al. (1994) pp 22,699-22,801. In order to determine whether the Clifford procedure gives appropriate errors, we compared simulated errors using a single least squares minimization and the weighted hyperbola method. The results, given in Figure 9 in Thomson et al. (1994), show that the two procedures give very similar error distributions.

D. Analysis of capabilities

The technique is capable of giving a source location and time-of-occurrence with errors able to be determined using analytical expressions. By defining a time tag in terms of three parameters on each measured pulse, timing errors can be found in terms of the variances of the pulses resulting from pulse waveshape differences. These timing errors have been found to be of the order of a few nanoseconds for waveshapes measured in a bandwidth of 2-4 MHz and digitized at 50 ns per sample. These errors are more than an order of magnitude lower than those found by Proctor (1971) for a similar system that located sources of VHF radiation from lightning. Location accuracies are limited presently by an uncertainty of about 20 ns in the calibration time delays (d_i in Thomson et al.,(1994)). If these could be reduced to less than the inherent timing errors arising from pulse-to-pulse waveshape variations, location accuracies of the order of 10 m are possible within the network.

E. Source of error

Error sources are described in Thomson et al. (1994). Timing errors arising from waveshape variations between stations are of the order of nanoseconds, as explained in Section III.D. The 20 ns errors in the calibration time delays dominate the errors in location and time-of-occurrence.

F. Advantages/shortcomings

The major advantage of the technique is that it defines methodology to obtain the location and time-of-occurrence of a source that reliably and rapidly converges to a solution. Timing errors are succinctly defined in order that errors in location and time-of-occurrence can be found. The goodness of the solution can be assessed using standard statistical tools such as χ^2.

G. References

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SECTION V - ADDITIONAL DOCUMENTATION

A. AVAILABLE DOCUMENTS:- 1. Paper

B. DATES FOR TECHNOLOGY DEVELOPMENT:- 1987-June 1994

C. FIRST PUBLICATION:- Thomson, E.M., P.J. Medelius, and S. Davis, System for locating the sources of wideband dE/dt from lightning, J. Geophys. Res., 99, 22,793-22,802, 1994.

D. OTHER PUBLICATIONS:- Nil

E. DEGREE OF TECHNOLOGICAL SIGNIFICANCE:- 1. Modification to existing technology

Signature Date